# WAVE EROSION OF A MASSIVE ARTIFICIAL COASTAL LANDSLIDE

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*Received 4 October 1996; Revised 1 September 1997; Accepted 1 October 1997*

## ABSTRACT

The Lone Tree landslide is located on the coast north of San Francisco, California, and is unusual in that it is positioned within the San Andreas fault zone. Its material ranges from mud through to boulders, which makes the slide particularly susceptible to mass movement. Movement of its western half increased following the Loma Prieta earthquake in 1989, closing an important highway for over a year, at which time a large cut-and-fill operation was undertaken to remove the upper portion of the slide so it would create no future disruption. Material cut from the upper slide was dumped below the highway, with the debris extending into the ocean. This created an artificial debris fill that is equivalent to a massive natural landslide, and a unique opportunity to monitor its erosion. Rainfall quickly eroded a series of rills into the face of the artificially created landslide, but the concentration of gravel and cobbles armoured these small channels, greatly reducing the rate of subsequent erosion. Waves cut away the toe, and the focus of this paper is on the development of a model to analyse the frequency of wave attack in terms of tide levels and wave conditions. A beach consisting of cobbles and boulders formed at the toe of the debris, offering partial protection and reducing the rate of continued erosion. In the short term, armouring of the rills and the development of a fronting beach have reduced the overall erosion of the debris and the transfer of sediment to the ocean. In the longer term, the formation of secondary slumps can be expected to renew the erosion. Eventually the morphology of the debris fill should approach the configuration of the natural landslide, an unmodified portion of which remains adjacent to the artificial fill. 

*Earth surf. process. landforms*, **23,** 415–428 (1998)
KEY WORDS: coastal; landslides; wave runup

## INTRODUCTION

A massive coastal landslide, named the Lone Tree landslide, is located about 15 km north of San Francisco (Figure 1). Its movement has been a problem for many years due to the disruption of the highway that is the main connecting link to coastal communities and to the Point Reyes National Seashore. The disruption became acute following the Loma Prieta earthquake of 17 October 1989, which increased the movement and destroyed the stretch of highway crossing the slide. The highway remained closed for a year and a half, requiring a lengthy rerouting of traffic.

After studying possible alternative solutions to the problem, the California Department of Transportation (CalTrans) decided to cut back the slope of the active portion of the slide in order to provide a more stable base for the highway. This involved removal of a large volume of rock and debris from the upper portion of the hillside and its placement as a fill at the base of the cliff, in effect creating a debris fill with many of the characteristics of a very large natural landslide. Much of this fill extended into the ocean where it has been attacked by waves, resulting in its erosion and the transfer of sediment to the marine environment. This raised concerns regarding the environmental impacts on marine life, particularly in the sanctuary that is part of the Point Reyes National Seashore some 15 km to the northwest (Figure 1). Such concerns were the motivation for establishing a monitoring programme to determine rates of sediment release from the debris fill and the fate of those sediments after entering the sea. A report was prepared by Hickey and Kachel (1994) detailing measurements of waves, currents and suspended sediments offshore from the slide, and reports also were prepared examining the biological impacts. The main objectives of our portion of the study were to document the processes important to the erosion of the debris fill and the release of sediment into the ocean. These

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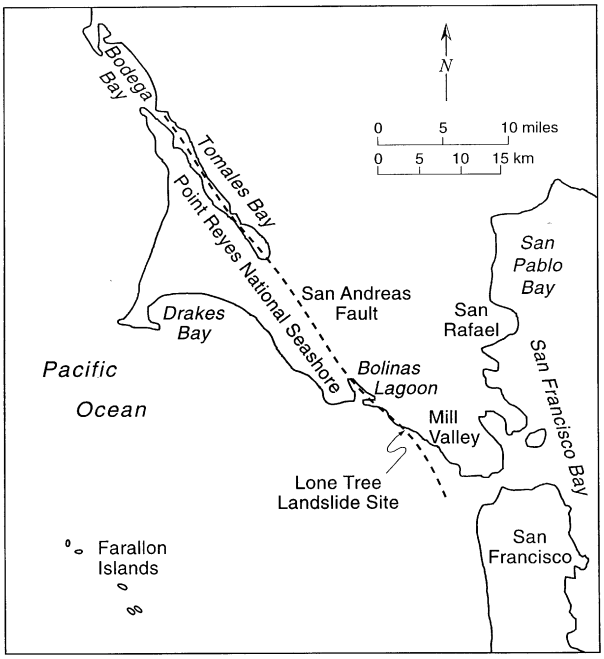


Figure 1. Regional map showing the location of the Lone Tree landslide about 15 km northwest of the entrance to San Francisco Bay. The dashed line gives the location of the San Andreas fault zone

processes are the same as those responsible for the erosion of natural landslides, including runoff from the surface of the debris due to rainfall and groundwater seepage, and wave erosion of the toe of the fill where it enters the sea. These objectives were met by a programme that included surveys of eroded rills, measurements of toe erosion rates, and the development of a model for toe erosion governed by waves and tidal elevations that is based on video measurements of the frequency of wave-swash attack (Komar, 1994). This paper concentrates mainly on a presentation of the toe-erosion model.

## LANDSLIDE OCCURRENCE AND MODIFICATIONS

The Lone Tree landslide is located in a stretch of coast that is steep and characterized by wave-eroded sea cliffs and rocky headlands. State Highway 1 roughly follows the trend of the coast and crosses the middle of the landslide. The slow movement of the slide through the decades, principally during the winter months of greatest rainfall, has disrupted the highway and required its frequent repair. The extent of the natural landslide is shown in the oblique aerial photograph of Figure 2, taken during March 1985. The photo shows patching of the highway undertaken during the spring of 1985, and indicates that mass movement requiring road repair was confined to the northwestern half of the total area of the natural landslide; this pattern persisted during at least two decades prior to the 1989 highway destruction. Figure 2 is also of interest in that it shows the presence of a continuous cobble/boulder beach at the base of the natural landslide, formed as a lag by the long-term wave erosion of its toe.

Increased mass movement occurred following the Loma Prieta earthquake of 17 October 1989, which was centred near the San Andreas fault zone where it passes to the northeast of Santa Cruz, about 100 km south of the Lone Tree landslide (Wagner, 1990). A number of landslides associated directly with this earthquake occurred near its epicentre, in the Santa Cruz Mountains (Spittler *et al.*, 1990) and in the coastal bluffs of Santa Cruz County (Sydnor *et al.*, 1990; Plant and Griggs, 1990). In contrast to the abrupt and rapid landsliding near the earthquake epicentre, the movement on the Lone Tree landslide was gradual and of a non-catastrophic nature. Instead, there was simply an intensification of the mass movement that continued for several months thereafter

 

Figure 2. An oblique aerial photograph of the Lone Tree landslide taken on 14 March 1985, showing the extent of the natural landslide and repairs on Highway 1 required by periodic mass movement within the western portion of the slide (CalTrans photograph)

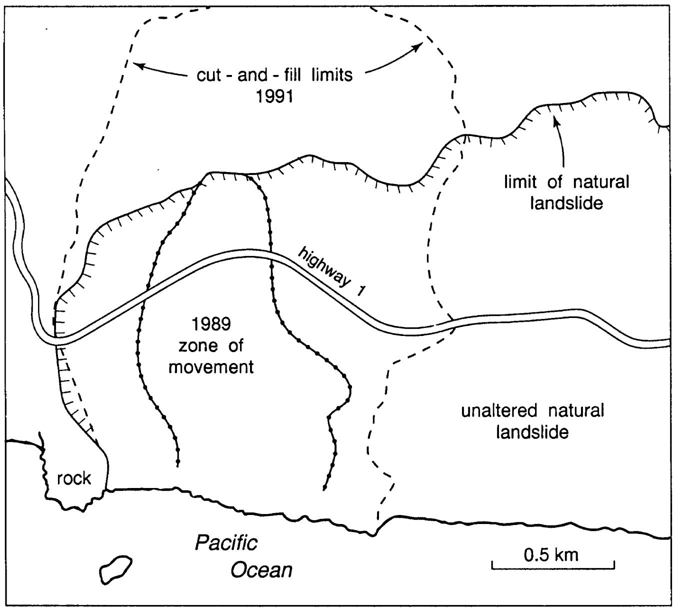


Figure 3. The extent of the natural Lone Tree landslide, and the portion affected by accelerated mass movement following the Loma Prieta earthquake of 17 October 1989. The cut-and-fill operation undertaken in 1991 modified the western half of the natural landslide

and progressively led to the destruction of the section of highway that crosses the slide. The aerial extent of the mass movement following the Loma Prieta earthquake is outlined in Figure 3, compared with the extent of the natural landslide. The movement again was confined to the northwestern half of the total extent of the slide, leaving the eastern half unaffected.

The destruction of the stretch of highway by the landslide interrupted traffic along the coast, and there was considerable pressure to reopen the highway. CalTrans was interested in stabilizing the area so as to minimize future disruptions, and after studying various options (Van Velsor, 1990), it was decided to reduce the slope of

 

Figure 4. The completed cut-and-fill operation, shown in a photograph taken on 20 February 1992. Winter rains have eroded a series of rills into the steeper slope of the fill, a secondary slump has developed, and waves have cut a toe in the debris fill forming a fronting beach of cobbles and boulders (CalTrans photograph)

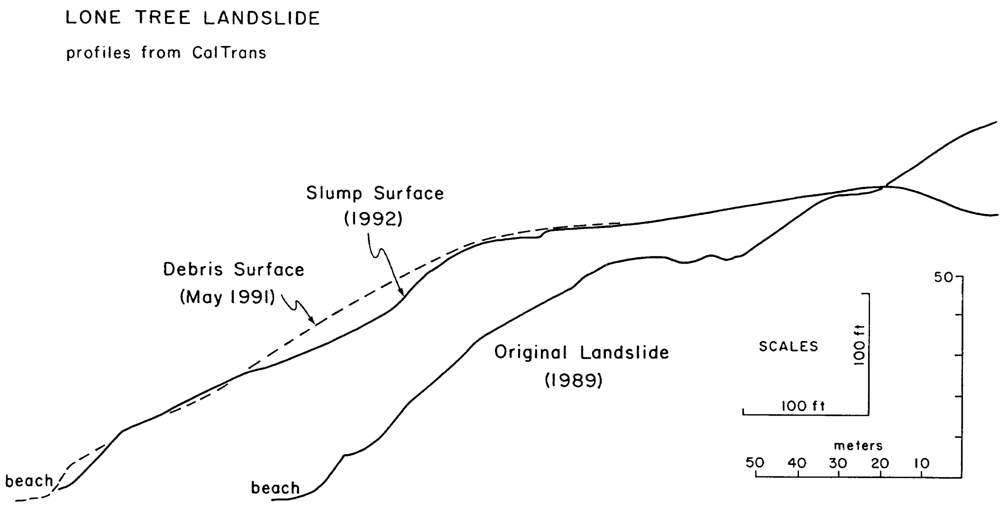


Figure 5. Profiles through the middle of the Lone Tree landslide, showing the original landslide surface with a fronting beach (1989), the surface soon after completion of the cut-and-fill operation (May 1991), and the subsequent modification by the development of a secondary slump and toe erosion by waves

the landslide by cutting back the upper half of the hillside and transferring the removed debris to the bottom. The extent of this cut-and-fill operation is outlined in Figure 3, determined from vertical aerial photographs; the operation altered only the western half of the slide, leaving the eastern half in its natural condition. The photograph of Figure 4 shows the completed project with the highway reopened. The project met its objective of stabilizing the highway in that there have been minimal subsequent repairs.

The operation resulted in the placement of an artificial debris fill into the ocean (Figure 4), the volume of the material moved having been estimated at about $1 \times 10^6 m^3$ (Van Velsor, 1990). The extent of this fill is indicated by the profiles in Figure 5, which includes a survey obtained in 1989 after renewed movement but prior to

 

modifications undertaken by CalTrans, a second survey obtained in May 1991 immediately after placement of the fill, and a third profile obtained in June 1992. The fill on average raised the ground level by about 15 m, and was a maximum of 35 m over the position of the former cobble/boulder beach at the toe of the natural landslide. The debris fill extended 60 to 70 m seaward of the former beach.

Soon after placement of the fill, fractures developed in the steep slope and the movement progressed to form a small secondary slump having the properties of a rotational landslide (Figure 4). The movement has been slow, occurring mainly during the winter months of greatest rainfall and higher wave activity which cuts away the toe of this secondary slide. Surface erosion and the formation of rills on the debris was particularly important during the first year after the cut-and-fill operation, and are readily apparent in Figure 4. Continued development of the rills has slowed, however, as cobbles armoured the channels and vegetation grew between the rills (Komar, 1994). The protrusion of the debris into the sea resulted in its immediate erosion by ocean waves. The toe was rapidly cut back (Figure 4) forming a steep slope with a new beach at its base consisting of cobbles and boulders released from the debris by the erosion. The 1992 survey in Figure 5 reveals the extent of toe retreat, which amounted to some 25 m since initial placement of the fill in 1991. The escarpment produced by wave erosion had reached a maximum elevation of 30 m. The erosion of the toe, the development of the secondary slump, and the formation of rills by runoff constitute the principal processes of degradation of the debris fill since completion of the project by CalTrans (Komar, 1994).

The Lone Tree landslide is of special interest in that it is located within the San Andreas fault zone, and this in large part accounts for its mobility. Its position within the fault zone is confirmed by the rocks at the site. Granites are present to the immediate west of the fault zone in the Point Reyes area, while the Cretaceous/ Jurassic Franciscan Formation is present throughout the area to the east (Galloway, 1977). For a distance of 2·5 to 4 km east of the fault zone, the Franciscan rocks consist exclusively of greywackes with subordinate shale, dipping toward the east at angles of 35 to 60°. In marked contrast, within the fault zone itself, the material is decomposed ultrabasic rocks, serpentine, pyroxine and other rock slices and boulders that have been termed ‘tectonic inclusions’ (Galloway, 1977). This describes the material found within the Lone Tree landslide, dominated by ultrabasic rocks with only a few scattered blocks of greywacke, and no granite. The presence of the Lone Tree landslide within the fault zone in large part accounts for its mobility in that serpentines, etc., in a jumbled mass are far more conducive to instabilities than are the granites to the west and layered greywackes of the Franciscan Formation to the east. This origin also accounts for the large range in grain sizes of material found within the landslide and debris fill. An extensive sampling programme (Komar, 1994) established that on average the debris consists of 16 per cent mud (clay and silt), 27 per cent sand and granules, 21 per cent pebbles, and 36 per cent cobbles through to boulders.

Earthquakes resulting from slippage along the San Andreas fault undoubtedly have been important in the development of the Lone Tree landslide, much as the Loma Prieta earthquake triggered landslides along the coast in the Santa Cruz area (Sydnor *et al*., 1990; Plant and Griggs, 1990). The great San Francisco earthquake of 18 April 1906 fractured the ground along the full length of the Olema valley (Figure 1), extending from Tomales Bay to Bolinas Lagoon (Galloway, 1977). The greatest measured horizontal movement on this strike-slip fault was 6 m near Point Reyes Station, about 25 km north of the landslide site. It is likely that this extreme earthquake, so close to the landslide, resulted in large-scale movement.

The morphology of the landslide suggests that it dates back in its inception to a century or more. This is apparent in the remaining unaltered southeastern portion of the slide, which has been much degraded by runoff with a number of small channels and one major gully cut into its surface. The slide is also densely covered by a mature growth of vegetation. Its toe has been cut back by waves over the decades, with the development of an extensive fronting beach that now acts as a buffer where the runup of the wave-swash is seldom able to reach the base of the landslide to produce further erosion. As a result, this old portion of the slide is now affected more by rain runoff and groundwater seepage, than by wave attack. While such features suggest a considerable age for the natural landslide, a rough estimate based on the development of taffoni weathering in rocks found on the fronting beach suggests that large-scale movement occurred during this century, probably at the time of the 1906 San Francisco earthquake (Komar, 1994).

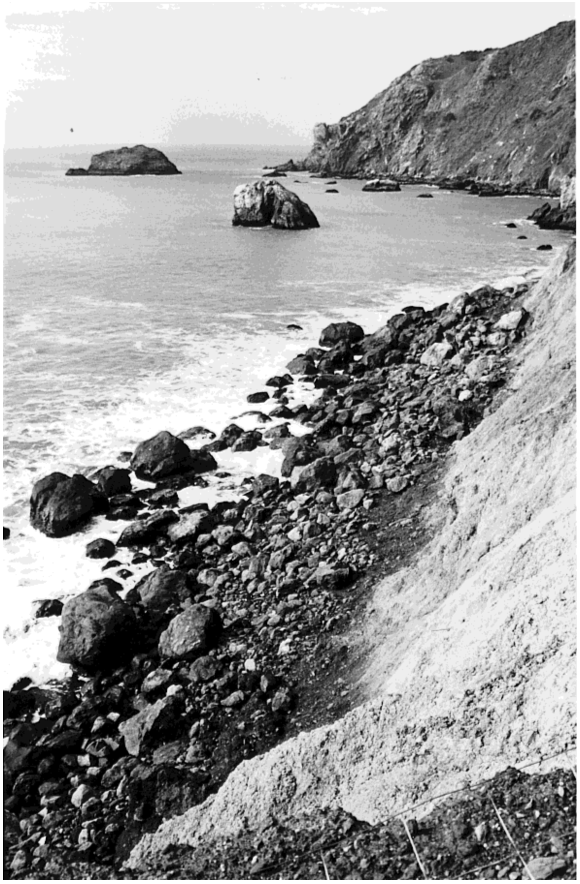

Figure 6. A 1992 photograph of the cobble/boulder beach that has developed in front of the eroding debris fill, now acting to partially protect the toe from continued wave erosion

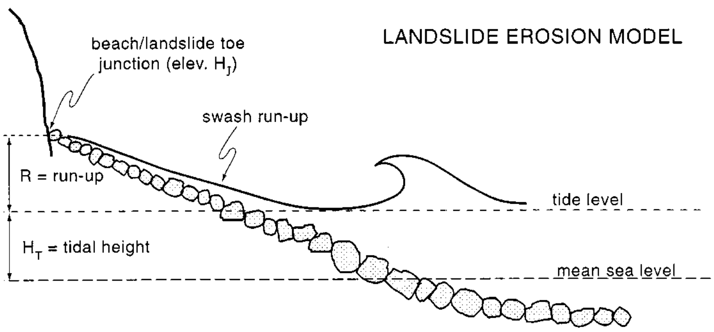


Figure 7. Diagram illustrating that the elevation achieved by water on the beach fronting the debris fill is dependent on the tidal height, $H_T$, plus the runup level, $R$, of the wash swash, and that erosion of the toe depends on its elevation $H_J$ relative to $H_T + R$

## TOE EROSION BY WAVES

During the monitoring year of this study, the most important erosion process acting on the Lone Tree debris fill was the action of waves cutting back its toe. As seen in the surveyed profiles of Figure 5, the fill material extended some 60 to 70 m seaward of the beach that had formed at the base of the natural landslide, placing the fill well into the water where it came under wave attack. The initial erosion, which occurred before monitoring

began, must have been rapid as an escarpment quickly formed along the seaward edge of the fill (Figure 4). A new beach began to accumulate at the base of the toe, consisting of cobbles and boulders eroded from the fill that are too large for the waves to carry away. Figure 6 shows the developing beach, which is now sufficiently wide to offer some protection to the debris from continued wave attack.

An important objective of the monitoring programme was the development of a model to analyse the frequency with which waves reach the toe of the debris and produce erosion. It was noted that at low tides and/or when the waves are small, the fronting beach has become sufficiently wide and high to provide full or partial sheltering from the wave runup. In contrast, during times of high tides and large storm waves, the runup of numerous waves can reach the base of the debris to cause erosion, and at such times there is noticeably more mud suspended in the immediate offshore water. The goal was to develop a model to predict wave attack as a function of the tidal elevation and runup levels of the waves. The components of the model are shown in Figure 7, where the runup height $R$ (a vertical distance) is added to the tidal height $H_T$, and their sum is compared with the elevation $H_J$ of the junction between the beach and the toe of the debris fill. Toe erosion occurs when

$$H_T + R \geq H_J \tag{1a}$$

or

$$(H_T + R) - H_J \geq 0 \tag{1b}$$

In our analyses we employed predicted tidal heights and times for the mouth of San Francisco Bay, which is only 15 km from the landslide site. The tides are classified as mixed, with a maximum spring-tide range of 2·4 m and neap-tide range of 1·5 m. It would be preferable to use measured tides in the analysis rather than predicted tides, in order to account for differences due to wind set-up, seasonal water temperature variations, etc. In the area of the study these factors are small, typically amounting to only a few centimetres, and therefore have not been included in this initial stage in the development of the toe-erosion model.

There have been many studies of wave runup, with measurements obtained on beaches and also on engineering structures such as the rocky slopes of jetties or seawalls (Douglass, 1990; Komar, 1998). The cobble beach developing in front of the debris fill has aspects of both. Several studies have shown that the runup elevation is a function of the wave height and period, the slope of the beach or structure, and the degree of roughness of the surface. The present analysis is based primarily on the results of Holman's (1986) investigation of wave runup on natural beaches, and of van der Meer and Stam (1992) who compiled laboratory data to examine wave runup on structures. Both studies found that the runup elevation $R$ achieved during 20 min of recording follows the relationship:

$$R = C\xi H_s \tag{2}$$

where $H_S$ is the significant wave height, the average of the highest one-third of the waves, $C$ is an empirical constant that depends on surface roughness (and associated permeability), and $\xi$ is the dimensionless Iribarren number defined as:

$$\xi = \frac{S}{(H_s / L)^{1/2}} \tag{3}$$

where $S$ is the slope of the beach face and $L$ is the wave length such that the ratio $H_S/L$ is the wave steepness. In

 

the laboratory studies of wave runup on structures, van der Meer and Stam (1992) found that with a surface roughened by cobbles and boulders, the proportionality coefficient $C$ in Equation 2 is reduced, there being less runup for a rough surface than for a smooth surface with the same wave conditions and beach slope. They found $C = 1{\cdot}5$ for runup on smooth slopes, while with rough surfaces $C = 0{\cdot}8$. In the above equations, the wave height $H_S$ and length $L$ are measured in deep water, in which case the wave length depends on the wave period $T$ according to the formula:

$$L = \frac{g}{2\pi} T^2 \tag{4}$$

where $g$ is the acceleration of gravity. Combining Equations 2 to 4 yields:

$$R = C\left(\frac{g}{2\pi}\right)^{1/2} S H_s^{1/2} T \tag{5}$$

for the runup elevation as a function of the wave height and period, the beach slope $S$ and of the roughness coefficient $C$.

The third factor in the toe-erosion model of Equation 1 is the elevation $H_J$ of the junction between the beach and the toe of the debris fill (Figure 7). This elevation was determined by surveys referenced to a nearby Coast and Geodetic Survey bench mark, so all elevations are relative to the National Geodetic Vertical Datum (NGVD), which is approximately equal to mean sea level at this site. The tidal elevations are referenced to the mean lower-low tides (MLLW), and therefore need to be re-referenced to also place them in terms of NGVD. This was done by including a 0·9 m factor, the difference between NGVD and MLLW for the San Francisco Bay tide gauge (Harris, 1981).

Surveys of the entire fronting beach established that the elevation $H_J$ of the beach-toe junction varied somewhat along the length of the beach, in part due to differences in beach-sediment grain sizes and degrees of protection offered by the fronting beach (Komar, 1994). There is a significantly greater accumulation of large boulders along the central portion of the beach, and they offer more protection from wave attack. A portion of the northwestern stretch of beach is nearly devoid of cobbles and boulders, with the debris toe protected only by a coarse-sand beach.

Measurements of wave runup on the cobble beach fronting the debris fill were obtained with videos in order to test and calibrate the toe-erosion model. During most of the study the video camera was placed at the upper edge of the eroding escarpment near the southeastern part of the debris fill, providing an excellent view of the fronting cobble beach as seen in Figure 6. A record obtained during any one day generally covered 1–2 h, during which time the tidal elevation changed while the wave conditions remained nearly constant. These long records were analysed in 10 min segments, which were then combined into 20 min segments in order to conform with the standard interval that has been used in analysing wave data and runup measurements. Our initial objective was to continuously monitor the runup and rundown of the swash on the cobble beach so as to permit a full statistical analysis of the process and water-level variations, much as accomplished by Holman (1986) on sandy beaches. However, this proved to be impossible on the Lone Tree cobble/boulder beach, due to its high roughness that hides the upper edge of the runup. Instead, we limited our measurements to the number of times $N$ the runup actually reached the toe of the debris during a 20 min interval under the combination of tidal elevation and wave conditions. With shorter wave periods, more waves reach the site during 20 min, so the measured $N$ was normalized to the total number of waves with the relationship:

$$N_{\%} = 100\frac{N}{1200/T} = \frac{NT}{12} \tag{6}$$

for the percentage $N_{\%}$ of waves reaching the toe during 20 min or 1200 s; $T$ is the wave period so that $1200/T$ is the total number of waves, and the 100 factor is included to convert the decimal fraction to a percentage. The toe-erosion analysis then becomes a comparison between $N_{\%}$ and Equation 1 which relates the water elevation to the toe elevation:

 

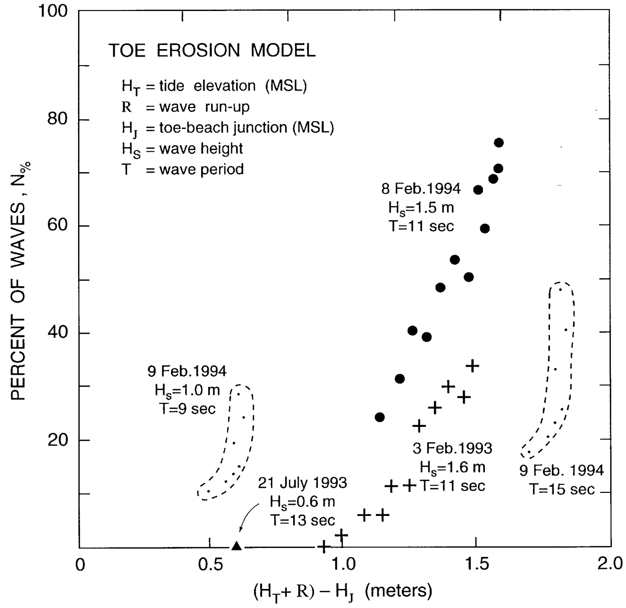


Figure 8. Analysis of wave runup measurements obtained with a video, giving the percentage, $N_{\%}$, of the waves reaching the toe within a 20 min interval compared to the water elevation governed by the tide, $H_T$, plus wave runup, $R$, versus the elevation of the beach–toe junction, $H_J$

$$N_{\%} = function\{(H_T + R) - H_J\} \tag{7}$$

Data for the wave conditions at times of runup measurements are needed in the model development. Wave data have been collected by the Coastal Data Information Program (CDIP) of Scripps Institution of Oceanography at a number of west-coast sites, the closest location to the Lone Tree landslide being south of the Farallon Islands, some 40 km seaward (Figure 1). The measurements are obtained with a wave-rider buoy positioned in 102 m water depth. As part of the monitoring programme, Hickey and Kachel (1994) installed instruments to measure wave heights, periods and directions just offshore from the Lone Tree landslide, in water depths of 11 to 15 m. Measurements were made twice daily during the summer, and four times daily during the winter. They found a good correlation between the significant wave heights and periods measured close to the landslide and waves measured by CDIP south of the Farallons, but with the heights at the landslide site being approximately half as large, apparently due to the more sheltered inshore position. In analyses of the runup measurements and model development, we relied on the wave data collected by Hickey and Kachel directly offshore. Later in this paper, in applying the model to an assessment of the long-term wave erosion of the debris, the extensive set of CDIP measurements is employed but converted to conditions at the site by using the correlation established by Hickey and Kachel.

Figure 8 shows the results of the wave runup analyses in terms of the toe-erosion model of Equation 7. In computations of the runup using Equation 5, the beach slope was taken as $S = 0{\cdot}20$, based on direct surveys of the cobble beach in the area viewed by the video. The roughness coefficient was set at $C = 0{\cdot}8$, this value being appropriate for a cobble beach according to the experimental results of van der Meer and Stam (1992). During most site visits, the combined tides and waves yielded insufficient water levels to reach the toe of the debris in the area where the video measurements were obtained. Although $N_{\%} = 0$ for those instances, the results are still relevant for establishing the toe-erosion model. The data point for 21 July 1993 is plotted in Figure 8, this being the instance for the highest water elevation that still yielded $N_{\%} = 0$.

Runup measurements obtained on 3 February 1993 and 8–9 February 1994 were the only recorded instances during which water elevations due to combined tides and wave runup exceeded the elevation of the beach–toe

 

junction. According to the 3 February 1993 and 8 February 1994 data (Figure 8), the 'threshold' condition of $N_{\%} = 0$ occurs at $H_T + R - H_J$ on the order of 0·6 to 0·8 m. It was expected that this threshold would be close to zero according to Equation 1, that is, the elevation $H_T + R$ achieved by the water is just equal to the elevation of the beach–toe junction, $H_J$. It is doubtful that values of tide levels and of the elevation of the toe could be this much in error. The results therefore suggest that the wave runup has been overestimated in applying Equation 5. This is likely in that the relationship is based almost entirely on laboratory experiments, with testing in the field limited to sandy beaches. The $C = 0{\cdot}8$ coefficient employed here is for the maximum runup during a 20 min interval, that is, the very highest of the 100 to 120 waves that occur. In the present application we are more interested in the average runup elevation, which would be significantly lower than the maximum. Furthermore, the $C = 0{\cdot}8$ value based on the laboratory experiments of van der Meer and Stam (1992) is for a beach consisting of a uniform cover of pebbles or cobbles. The cobble/boulder beach fronting the Lone Tree debris fill is decidedly non-uniform (Figure 6), and this also acts to reduce the value of $C$. In particular, the larger boulders tend to be at the bottom of the sloping beach where they act to dissipate the wave energy before its development into swash. These boulders have the greatest effect during lower tidal stages, at which time the value of $C$ could be substantially lower than the 0·8 value based on laboratory results. The value of $C$ could be expected to vary with the tide, increasing as the tidal elevation increases. According to Equation 4, this variability in $C$ would dissipate the runup at low to mid-tides, while permitting greater runup at the higher tidal elevations when the boulders at the base of the beach are fully submerged. This might account for the dramatic increase in $N_{\%}$ seen in Figure 8 with increasing water elevations. Inclusion of this variability would require further refinements of the model, and in particular the collection of additional data under a greater range of tide and wave conditions.

Beyond the 'threshold' level with $N_{\%} = 0$, there is a systematic and rapid increase in $N_{\%}$ with the water elevation (Figure 8). This is documented by the runup data gathered on 3 February 1993 and on 8 February 1994. At times of high tides combined with winter waves, the measurements show that some 80 per cent of the waves reaching the beach generate sufficient runup to reach the toe of the debris; with wave periods of 10 to 15 s common at this site, this means that some 50 to 100 waves strike the toe during a 20 min interval, potentially causing erosion. The videos typically show that the large waves arrive in groups, so for a minute or two virtually every wave strikes the toe, but this is followed by intervals during which only low waves arrive, none of which produce sufficient runup to reach the toe. Unfortunately, our measurements included in Figure 8 are limited to rather modest tides and wave conditions (the maximum $H_S$ during our runup measurements was 1·6 m, whereas major storms generate waves with $H_S$ on the order of 2 to 3 m). Under high storm waves, it can be expected that $N_{\%}$ would be on the order of 100, with the runup of virtually every wave reaching the toe of the debris fill.

The runup data collected on 3 February 1993 and on 8 February 1994 show some disagreement as to the percentage of waves reaching the toe of the debris for the same water elevation. Without the collection of additional measurements, we cannot be certain as to the cause of this discrepancy. Although there is a degree of subjectivity in assessing from videos whether or not runup from a wave reaches the toe, the measurement is sufficiently certain that this cannot account for the difference. There could be some difference between the actual tide elevation and that predicted, but this would be expected to be smaller than the 0·2 to 0·3 m difference in the horizontal positions of the data along the $(H_T + R) - H_J$ axis of Figure 8. Instead, the problem again is likely in the evaluation of the runup from the wave measurements. With Equation 5 the evaluation is sensitive to the value of the wave height, $H_S$, and especially to the wave period, $T$. The measured wave periods for both 3 February 1993 and 8 February 1994 were $T = 11$ s, but if the period on 3 February was actually 10 s, which is well within the uncertainty of the data (Hickey and Kachel, 1994), the level of runup would have been less and the $(H_T + R) - H_J$ values for the two days would have yielded a close correspondence in data trends. This problem is illustrated further by the runup measurements obtained on 9 February 1994. The dominant wave period was $T = 9$ s, but as can be seen in Figure 8, computations of the runup with this period yield a marked discrepancy with the other measurements. The Coastal Data Information Program (CDIP) provides complete spectra of wave measurements at the Farallon Islands, and this permits a more detailed examination of the wave conditions. Specifically, on 9 February 1994 the spectra reveal that more than one wave train was present. Although the 9 s waves formed the dominant energy peak in the spectra, there was a second important energy peak at 15 s. Accordingly, the runup measurements were also analysed using this longer wave period, and it is seen in Figure 8 that this shifts the data to $(H_T + R) - H_J$ levels that are too high for agreement with the other data

 

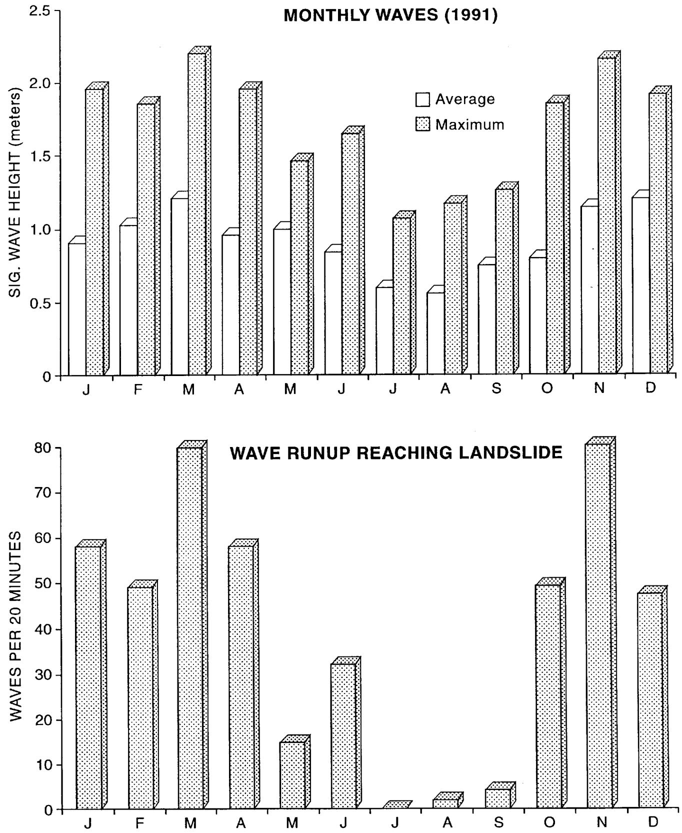


Figure 9. Histogram of the monthly wave climate for 1991, giving the monthly average and maximum significant wave heights for the Lone Tree landslide site. The lower histogram is the calculated number of wave swash events that would be high enough, when superimposed on a high tide of $H_T = 0{\cdot}9$ m MSL, to reach the toe of the debris fill during a 20 min interval when the waves are at their maximum sizes according to the upper histogram

sets. The results indicate that when two or more significant wave trains are present, a more complex analysis of wave runup is needed, which requires further research and data collection.

It became apparent during our observations that the runup of waves and toe erosion is greater along the northwestern portion of the beach than along the southeastern stretch where the video measurements were obtained. Toe erosion in the northwest section occurs where the beach is a uniform coarse sand with few cobbles and boulders. The elevation of the toe, $H_J$, is slightly higher than in the area of video measurements (2·5 versus 2·2 m), and the beach slope is lower ($S$ = 0·18 versus 0·20); these differences would be expected to decrease $N_{\%}$ relative to the impacts in the area of video measurements. The dominant factor in permitting more waves to reach the toe of the debris fill must be the roughness factor $C$ of the sandy beach versus the cobble beach where the videos were obtained. According to the laboratory results of van der Meer and Stam (1992), $C$ = 1·5 for a sandy beach while with rough slopes of pebbles or cobbles they obtained $C$ = 0·8. According to the equation for evaluating the runup $R$, this alone would account for a 1·5/0·8= 1·9 factor difference in the runup elevation, other factors being the same. As discussed above, the 0·8 factor is probably too high for the cobble beach fronting the debris fill, while the 1·5 factor for the sandy beach should be reasonably correct. Thus, the ratio of the roughness coefficients and of the corresponding runup elevations for the contrasting beaches could be substantial, probably on the order of 3 to 4. This difference would account for the observation that wave runup frequently reaches the toe of the debris in the northwestern portion, where the beach consists of sand, at times when the runup falls well short of the toe where it is protected by the cobble beach.

## SEASONALITY OF TOE EROSION

Wave conditions are more severe during the winter than in the summer, while the tides are much the same. It follows that the runup can be expected to reach the toe of the debris far more frequently during the winter than in the summer, producing more erosion. An assessment of this seasonal difference is made in Figure 9. The upper histogram is the monthly wave climate for 1991, based on waves measured at the Farallon Islands by CDIP but then modified to the lower energy offshore from the Lone Tree landslide according to the correlation found by Hickey and Kachel (1994). The upper histogram includes the average wave height for each month, and also the maximum significant wave height that occurred in the daily records for the individual months. For the most part the results show the expected greatest wave heights during the winter, becoming lowest in July and August.

The lower histogram of Figure 9 gives the expected number of wave runup events that reach the toe of the debris in the area of video measurements during a 20 min time interval, according to the model results found in Figure 8. The data trend from 3 February 1993 with a 'threshold' of $(H_T + R) - H_J = 0{\cdot}8$ m was used in the analysis, the results being more conservative than the trend given by the 8 February 1994 data. In making the calculations for the lower histogram in Figure 9, it was assumed that $H_T = 0{\cdot}9$ m above mean sea level (NGVD), something of an average of the higher-high tidal levels, about 0·25 m lower than the highest spring tides. The analysis shows that the average waves of the summer would not yield sufficient runup to reach the toe of the debris when superimposed on an average higher-high tide, and even during average winter wave conditions the runup barely reaches the toe of the debris. Instead, higher than average waves are required to produce toe erosion, and it can be expected that storms will be the most important element. This is indicated in the lower histogram of Figure 9, with the calculations of $N$ based on the highest wave conditions experienced during each month of 1991 (upper histogram). It is seen that during the summer months of July to September, even the largest waves of the month are barely adequate to produce runup that results in toe erosion in the area of the cobble beach. In contrast, the runup of winter storm waves produces water elevations well in excess of the toe elevation. It follows that significantly more erosion can be expected from wave attack of the debris during the winter than in the summer. Erosion in the winter can take place along nearly the full length of the debris toe, while erosion during the summer is limited to the small stretch of toe behind the coarse-sand beach which offers less protection.

That more erosion occurs during the winter than in the summer is apparent from the quantities of suspended sediments measured offshore (Hickey and Kachel, 1994). However, the amount of toe erosion by the swash of waves during any one day is actually very small, even when high tides combine with storm waves. The material composing the debris – cobbles and boulders held together by cohesive clay – is highly resistant to wave attack. Therefore, it was not possible to simply relate $N_{\%}$ to a measured erosion retreat of the debris toe during those 20 min, or even during a day or week. We did establish that there is much more erosion during the winter than in the summer, through the placement of stakes on the surface of the debris to monitor the retreat of the upper edge of the toe escarpment (Komar, 1994). There is a significant spatial variability in erosion along the width of the debris fill. Most notably, the stable portion of the debris retreated more slowly than the unstable area of the secondary slump where the interpretation of the results from the stakes is difficult due to the continued movement of the secondary slump. This slump is slowly moving toward the sea, where it is cut away by the wave runup, such that the position of the escarpment remains roughly the same. According to our measurements, erosion of the toe in the slump area amounted to some 1·5 to 3 m during two months in the winter of 1993–94, while erosion of the toe in the more stable portions of the debris fill during the same period averaged less than 1 m. Continued measurements through the summer of 1994 showed almost no retreat of the escarpment, either in the area of the secondary slump or in the more stable area.

## SUMMARY AND DISCUSSION

The overall objective of this study has been to monitor the erosion of the Lone Tree debris fill, formed when a natural landslide was cut away and the removed material was placed as debris extending into the ocean. The concern was that the large-scale release of sediment from erosion of the debris would adversely affect marine

 

life in nearby sanctuaries. The impacts thus far have been minimized by the self-armouring response of the debris to the erosion processes. Rain runoff during the first winter following the cut-and-fill operation rapidly eroded rills into the surface of the debris, but these small channels became armoured by accumulated gravel and cobbles, resulting in low subsequent rates of erosion. In a similar fashion, waves quickly cut a toe into the base of the debris, but the erosion left behind a fronting beach of cobbles and boulders that now provides considerable protection to the toe from continued wave attack.

The monitoring of this artificial debris fill has provided a unique opportunity to investigate the early stages of erosion of natural coastal landslides. A model has been developed, based on video records of wave runup, that relates the frequency with which the wave-swash reaches the toe of the debris to the elevation of the tide and to heights and periods of the offshore waves that determine the runup level above the tide. Although there are shortcomings in the model, for the most part the results show the expected pattern with the cobble beach offering protection to the debris toe during low-water elevations, but with a rapid increase in frequency of wave attack once the water exceeds a ‘threshold’ level. Improved predictions will have to await refinements based on more detailed considerations of wave runup and analyses that include additional factors that affect the mean-water level. The model confirms that there is a much greater intensity of wave attack of the debris toe during the winter compared with the summer, and the expected higher rate of toe erosion during the winter has been demonstrated by measurements of the retreat of the top of the escarpment determined from series of stakes.

With the rills having become armoured and with the development of a cobble beach protecting the toe of the fill, erosion of the debris can be expected to continue at a slow rate with relatively small quantities of sediment introduced into the ocean. However, the quantities delivered will depend in part on the rate of continued slumping of the front of the debris, a process that regenerates rill formation and delivers sediment to the fronting beach where it is eroded by waves. Thus far the movement of the secondary slump has been slow, but there is the possibility that it could accelerate and even fail catastrophically, in which case there would be a rapid and substantial input of sediment into the ocean.

It can be expected that continued slumping of the steep face of the debris will progressively reduce its slope, approaching the overall slope of the natural landslide, a portion of which remains adjacent to the artificial debris fill. At some stage the numerous small rills should coalesce into a few large gullies that are better able to transport the gravel and cobbles. Runoff and groundwater will become increasingly important as observed on the natural landslide, especially when the beach fronting the debris fill grows to the extent that it offers substantial protection from wave erosion except during the most extreme conditions of high tides and waves generated by severe winter storms. All of these processes acting to degrade the debris fill are slow, so it can be expected that many decades will pass before the fill takes on the approximate morphology of the natural landslide.

## ACKNOWLEDGEMENTS

This work was undertaken with support from the California Department of Transportation. I would like to thank Mr James Cunningham of CalTrans, who provided me with surveys and aerial photographs, and Dr Barbara Hicky of the University of Washington for supplying me with wave data. Considerable thanks are owed to Shyuer-Ming Shih, Peter Ruggiero, Paul Salop and Mark Lorang, students who assisted me in conducting the field work.

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